Department I - C Plus Plus

Modern and Lucid C++
for Professional Programmers

Week 12 – Dynamic Polymorphism

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- **You can safely employ virtual dispatch**
- **You can explain the dangers when working with value semantics and dynamic dispatch**
- **You can use virtual base classes with std::unique_ptr**

Topics

- **Recap Week 11**
- **Dynamic Polymorphism**
  - Motivation for Inheritance
  - Review of Inheritance
  - Shadowing vs. Virtual Member Functions
  - Possible Problems
  - Guidelines

Recap Week 11

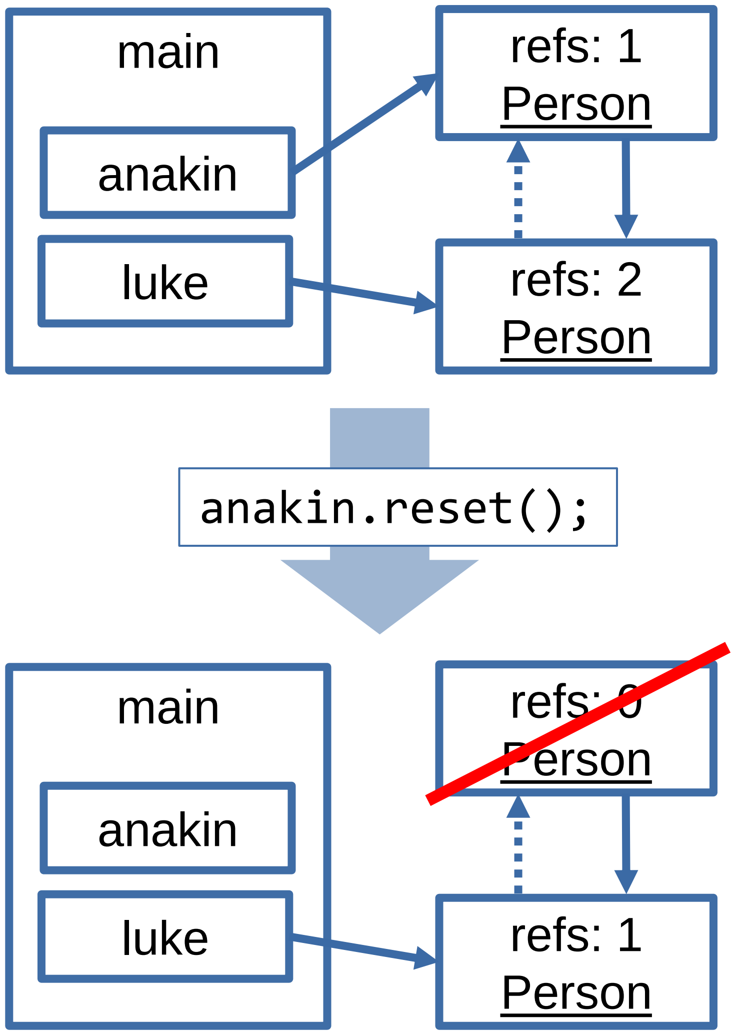
Ostschweizer Fachhochschule

```
auto factory(int i) -> std::unique_ptr<X> {
    return std::make_unique<X>(i);
}
```

- `std::unique_ptr<T>` obtained with `std::make_unique<T>()`
- `std::shared_ptr<T>` obtained with `std::make_shared<T>()`
- `std::make_unique<T>()` and `std::make_shared<T>()` are factory functions
- With these smart pointers you don't have to call `delete ptr;` yourself
- Still: Always prefer storing a value locally as value-type variable (stack-based or member)

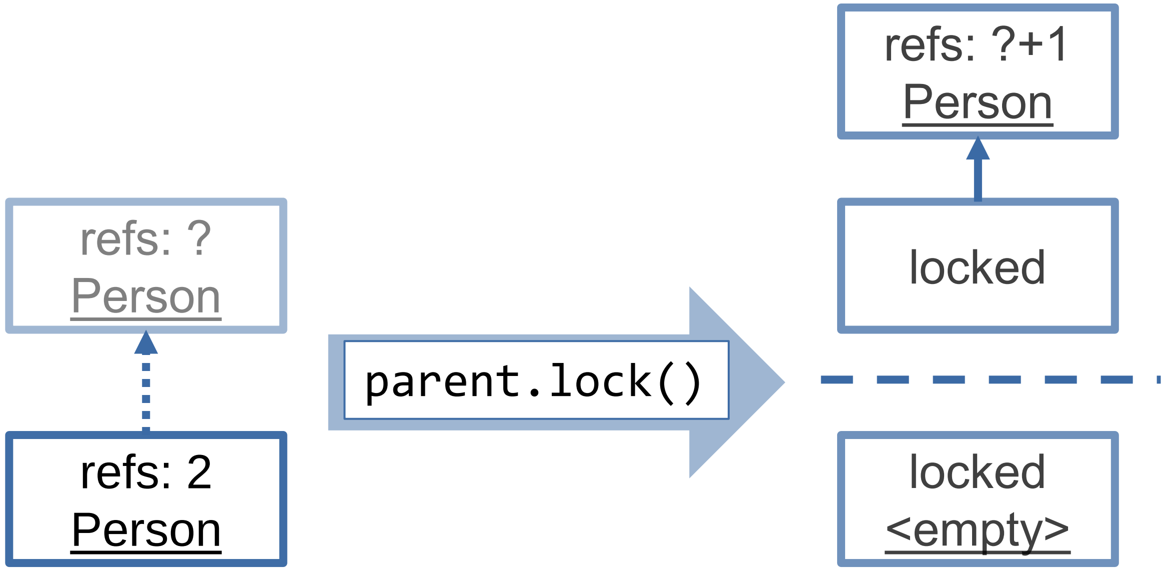
- **The `std::shared_ptr` cycles need to be broken**

```
struct Person {
  std::shared_ptr<Person> child;
  std::weak_ptr<Person> parent;
};

auto main() -> int {
  auto anakin = std::make_shared<Person>();
  auto luke = std::make_shared<Person>();
  anakin->child = luke;
  luke->parent = anakin;
  //...
}
```



- **A `std::weak_ptr` does not know whether the pointee is still alive**
  - `std::weak_ptr::lock()` returns a `std::shared_ptr` that either points to the alive pointee or is empty

```
struct Person {
  std::shared_ptr<Person> child;
  std::weak_ptr<Person> parent;

  auto Person::acquireMoney() const -> void {
    auto locked = parent.lock();
    if (locked) {
      begForMoney(*locked);
    } else {
      goToTheBank();
    }
  }
};
```



Dynamic Polymorphism

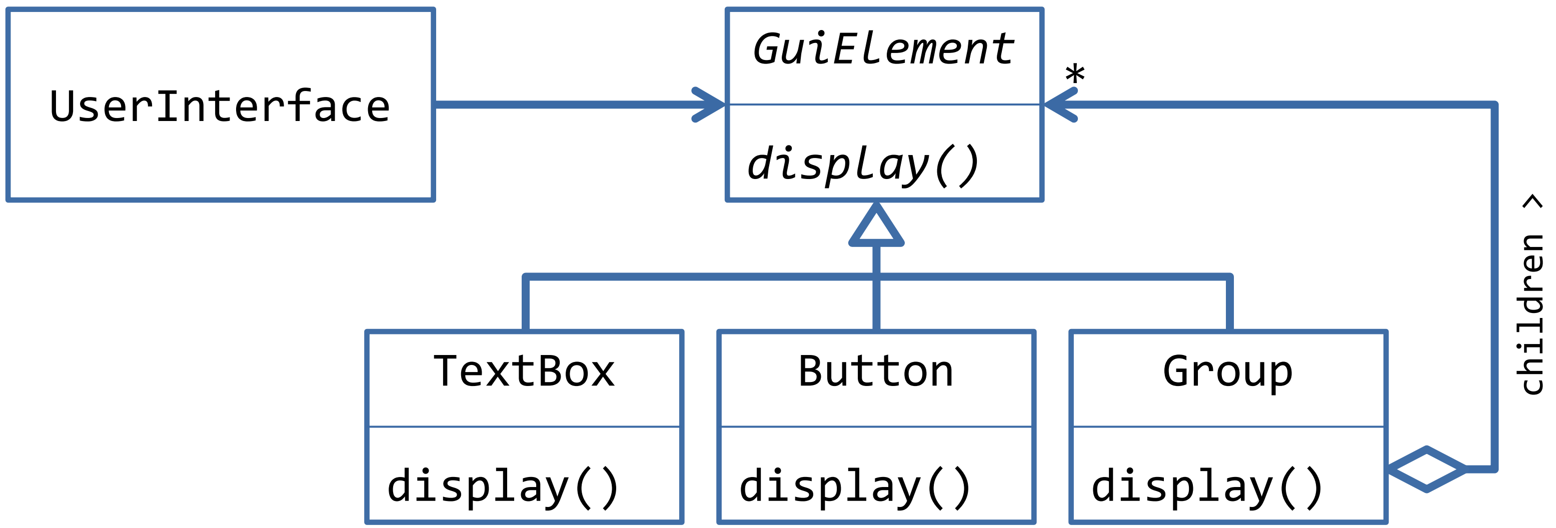
- **Mix-in of functionality from empty base class**
  - Often with own class as template argument (CRTP) e.g., `boost::equality_comparable<T>`
  - No inherited data members, only added functionality

```
struct Date : boost::equality_comparable<Date> {
  //...
};
```

- **Adapting concrete classes**
  - No additional own data members
  - Convenient for inheriting member functions and constructors

```
template<typename T, typename Compare>
struct indexableSet : std::set<T, Compare> {
  //...
};
```

- **Implementing a design pattern with dynamic dispatch**
  - e.g., Strategy, Template Method, Composite, Decorator
  - Provide common interface for a variety of dynamically changing or different implementations
  - Exchange functionality at run-time
- **Base class/interface class provides a common abstraction that is used by clients**

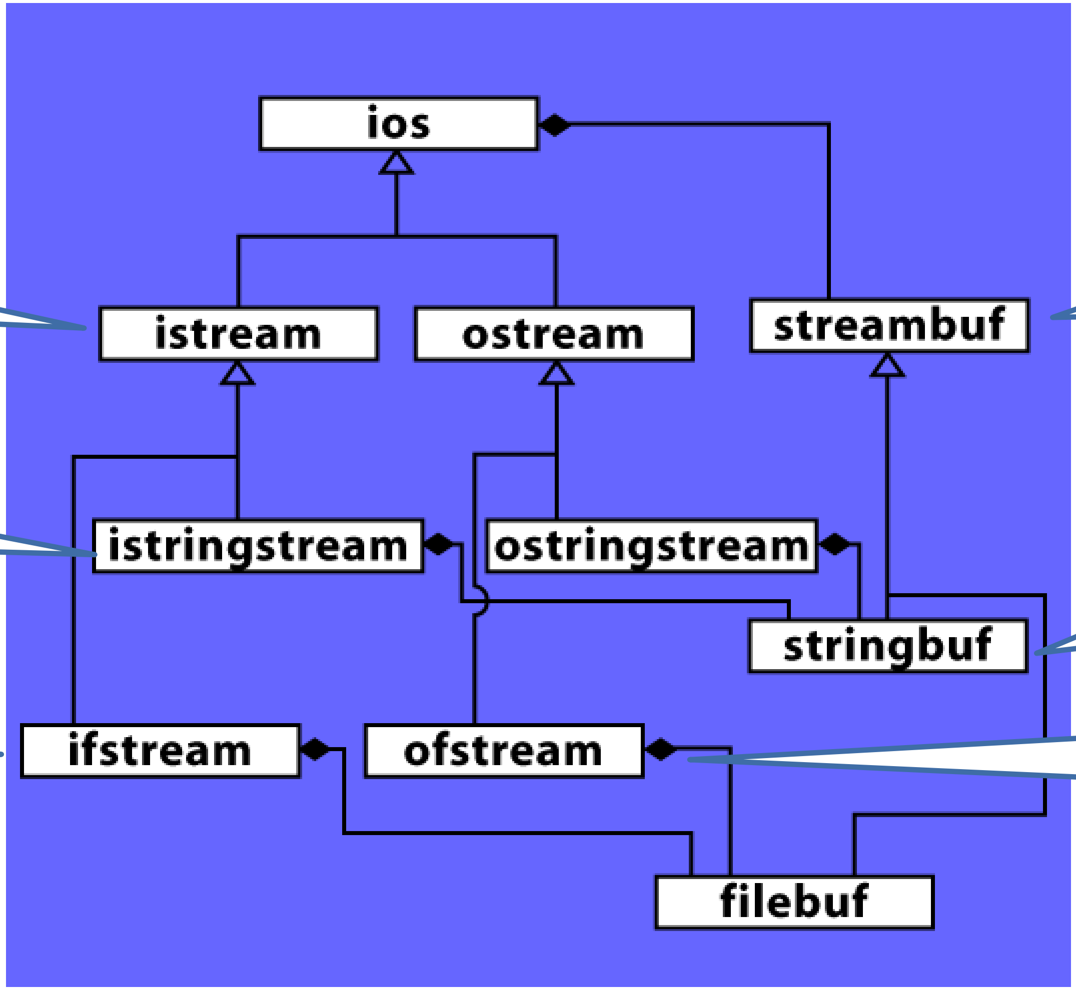


Simplified Hierarchy of `iostreams`

abstraction for formatted input

concrete class for string input

concrete class for file input



abstraction for formatted output

concrete class for string output

concrete class for file output

Image source: http://users.monash.edu/~cema/courses/CSE2305/Topics/12.23.CaseStudy/html/ioHierarchy.gif

Inheritance Syntax (Recap)

```cpp
class Base {};
class DerivedPrivateBase : Base {};
struct DerivedPublicBase : Base {};
```

- **In class definition after class name and a colon put the list of base classes, if any**
  - Sequence is important -> sequence of initialization if multiple base classes

```cpp
class Base {};
struct MixIn {};
struct MultipleBases : public Base, private MixIn {};
```

- **With interface inheritance, base class must be public**
  - Private inheritance is possible, but only useful for mix-in classes that provide friend function
- **Private inheritance can be used for some mix-in base classes that only add friend functions, like boost/operators.hpp helper classes**
  - Most often, private base classes (with members) are wrong design!

Initializing Multiple Base Classes

- **Base constructors can be explicitly called in the member initializer list**
  - If a constructor of a base is omitted its default constructor is called
- **You should put base class constructor class before the initialization of members**
  - The compiler enforces this rule, even though you can put the list of initializers in wrong order

```
class DerivedWithCtor : public Base1, public Base2 {
  int mvar;
public:
  DerivedWithCtor(int i, int j) :
      Base1{i}, Base2{}, mvar{j} {}
};
```

What is the Output?

```
struct Base1 {
  explicit Base1(int value) {
    std::cout << "Base1 with argument " << value << "\n";
  }
};

struct Base2 {
  Base2() { std::cout << "Base2\n"; }
};

class DerivedWithCtor : public Base1, public Base2 {
  int mvar;
public:
  DerivedWithCtor(int i, int j)
      : mvar{j}, Base2{}, Base1{mvar} {}
};

auto main() -> int {
  DerivedWithCtor dwc{1, 2};
}
```

- **C++' default mechanisms support value classes with copying/moving and deterministic lifetime**
- **Operator and function overloading and templates allow polymorphic behavior at compile time**
  - This is often more efficient and avoids indirection at run-time
- **Dynamic polymorphism needs object references or (smart) pointers to work**
  - Syntax overhead
  - The base interface must be a good abstraction
  - Copying carries the danger of slicing (an object is only copied partially)
- **Implementing design patterns for run-time flexibility: i.e., Strategy, Composite, Decorator**
  - Client code uses abstract interface and gets parameterized/called with reference to concrete instance
- **But: if run-time flexibility is not required, templates can implement many patterns with compile-time flexibility as well**

- **If a function is reimplemented in a derived class, it shadows its counterpart in the base class**
- **However, if accessed through a declared base object, the shadowing function is ignored**
- **What is the output of this example?**

```
struct Base {
  auto sayHello() const -> void {
    std::cout << "Hi, I'm Base\n";
  }
};

struct Derived : Base {
  auto sayHello() const -> void {
    std::cout << "Hi, I'm Derived\n";
  }
};
```

```
auto greet(Base const & base) -> void {
  base.sayHello();
}

auto main() -> int{
  Derived derived{};
  greet(derived);
}
```

- **Dynamic polymorphism requires base classes with `virtual` member functions**
  - `virtual` member functions are bound dynamically
- **What is the output of this example?**

```
struct Base {
  virtual auto sayHello() const -> void {
    std::cout << "Hi, I'm Base\n";
  }
};

struct Derived : Base {
  virtual auto sayHello() const -> void {
    std::cout << "Hi, I'm Derived\n";
  }
};
```

```
auto greet(Base const & base) -> void {
  base.sayHello();
}

auto main() -> int {
  Derived derived{};
  greet(derived);
}
```

- **`virtual` is inherited and can be omitted in the derived class**
- **It is possible to mark an overriding function with `override`**
  - Similar to the Java annotation `@Override` the compiler will produce an error if the annotated function does not override a member function in a base class

```cpp
struct Base {
  virtual auto sayHello() const -> void {
    std::cout << "Hi, I'm Base\n";
  }
};

struct Derived : Base {
  auto sayHello() const override -> void {
    std::cout << "Hi, I'm Derived\n";
  }
};
```

```cpp
auto greet(Base const & base) -> void{
  base.sayHello();
}

auto main() -> int {
  Derived derived{};
  greet(derived);
}
```

- **To override a virtual function in the base class the signature must be the same**
- **Constness of the member function belongs to the signature**

```
struct Base {
  virtual auto sayHello() const -> void {
    std::cout << "Hi, I'm Base\n";
  }
};

struct Derived : Base {
  auto sayHello() override -> void{
    std::cout << "Hi, I'm Derived\n";
  }
};

struct OtherDerived : Base {
  auto sayHello(std::string name) const override -> void {
    std::cout << "Hi " << name << ", I'm OtherDerived\n";
  }
};
```

- **Value Object**
  - Class type determines function, regardless of virtual

- **Reference**
  - Virtual member of derived class called through base class reference

```
struct Base {
  virtual auto sayHello() const -> void;
};

struct Derived : Base {
  auto sayHello() const -> void;
};

auto greet(Base base) -> void {
  //always calls Base::sayHello
  base.sayHello();
}
```

```
struct Base {
  virtual auto sayHello() const -> void;
};

struct Derived : Base {
  auto sayHello() const -> void;
};

auto greet(Base const & base) -> void {
  //calls sayHello() of the actual type
  base.sayHello();
}
```

- **Smart Pointer**
  - Virtual member of derived class called through smart pointer to base class

```
struct Base {
  virtual auto sayHello() const -> void;
};

struct Derived : Base {
  auto sayHello() const -> void;
};

auto greet(std::unique_ptr<Base> base) {
  //calls sayHello() of the actual type
  base->sayHello();
}
```

- **Dumb Pointer**
  - Virtual member of derived class called through base class pointer

```
struct Base {
  virtual auto sayHello() const -> void;
};

struct Derived : Base {
  auto sayHello() const -> void;
};

auto greet(Base const * base) -> void {
  //calls sayHello() of the actual type
  base->sayHello();
}
```

Mixed Example

```cpp
struct Animal {
  auto makeSound() -> void {cout << "---\n";}
  virtual auto move() -> void {cout << "---\n";}
  Animal() {cout << "animal born\n";}
  ~Animal() {cout << "animal died\n";}
};

struct Bird : Animal {
  virtual auto makeSound() -> void {cout << "chirp\n";}
  auto move() -> void {cout << "fly\n";}
  Bird() {cout << "bird hatched\n";}
  ~Bird() {cout << "bird crashed\n";}
};

struct Hummingbird : Bird {
  auto makeSound() -> void {cout << "peep\n";}
  virtual auto move() -> void {cout << "hum\n";}
  Hummingbird() {cout << "hummingbird hatched\n";}
  ~Hummingbird() {cout << "hummingbird died\n";}
};
```

```cpp
auto main() -> int {
  cout << "(a)--------------------------------\n";
    Hummingbird hummingbird;
    Bird bird = hummingbird;
    Animal & animal = hummingbird;
  cout << "(b)--------------------------------\n";
    hummingbird.makeSound();
    bird.makeSound();
    animal.makeSound();
  cout << "(c)--------------------------------\n";
    hummingbird.move();
    bird.move();
    animal.move();
  cout << "(d)--------------------------------\n";
}
```

- **What is the output?**
- **What is bad with this code's design?**

Abstract Base Classes: Pure Virtual

- **There are no interfaces in C++**
- **A pure virtual member function makes a class abstract**
- **To mark a virtual member function as pure virtual it has zero assigned after its signature**
  - = 0
  - No implementation needs to be provided for that function

```
struct AbstractBase {
  virtual void doitnow() = 0;
};
```

- **Abstract classes cannot be instantiated (like in Java)**

```
AbstractBase create() {
  return AbstractBase{};
}
```

Destructors (non-virtual)

- **Classes with virtual members require a virtual Destructor**
  - Otherwise when allocated on the heap with `std::make_unique<Derived>` and assigned to a `std::unique_ptr<Base>` only the destructor of Base is called

```cpp
struct Fuel {
  virtual auto burn() -> void = 0;
  ~Fuel() { std::cout << "put into trash\n"; }
};

struct Plutonium : Fuel {
  auto burn() -> void { std::cout << "split core\n"; }
  ~Plutonium() { std::cout << "store many years\n"; }
};

auto main() -> int {
  std::unique_ptr<Fuel> surprise = std::make_unique<Plutonium>();
}
```

```
Output:
put into trash
```

- **Classes with virtual members require a virtual Destructor**
  - Otherwise when allocated on the heap with `std::make_unique<Derived>` and assigned to a `std::unique_ptr<Base>` only the destructor of Base is called

```
struct Fuel {
  virtual auto burn() -> void = 0;
  virtual ~Fuel() { std::cout << "put into trash\n"; }
};

struct Plutonium : Fuel {
  auto burn() -> void { std::cout << "split core\n"; }
  ~Plutonium() { std::cout << "store many years\n"; }
};

auto main() -> int {
  std::unique_ptr<Fuel> surprise = std::make_unique<Plutonium>();
}
```

```
Output:
store many years
put into trash
```

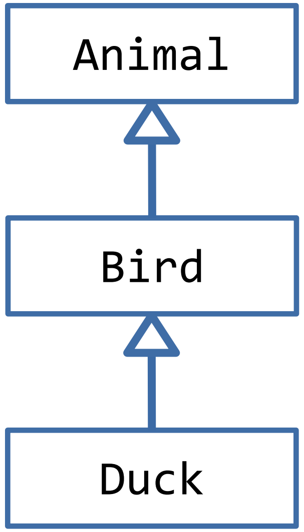
Destructors with `std::shared_ptr`

- **std::shared_ptr memorize the actual type and know which destructor to call**

```
struct Fuel {
  virtual auto burn() -> void = 0;
  ~Fuel() { std::cout << "put into trash\n"; }
};

struct Plutonium : Fuel {
  auto burn() -> void { std::cout << "split core\n"; }
  ~Plutonium() { std::cout << "store many years\n"; }
};

auto main() -> int {
  std::shared_ptr<Fuel> surprise = std::make_shared<Plutonium>();
}
```

```
Output:
store many years
put into trash
```

- **Inheritance introduces a very strong coupling between subclasses and their base class**
  - You can hardly change the base class
- **API of base class must fit for all subclasses**
  - Very hard to get right
- **Conceptual hierarchies are often used as examples but are usually very bad software design, e.g., animal->bird->duck**
- **Only one standard library part (the oldest) uses inheritance with dynamic polymorphism: iostreams**



- **Assigning or passing by value a derived class value to a base class variable/parameter incurs object slicing**
  - Only base class member variables are transferred

```
struct Base {
  int member{};
  explicit Base(int initial) :
      member{initial}{}
  virtual ~Base() = default;
  virtual auto modify() -> void { member++; }
  auto print(std::ostream & out) -> void const;
};

struct Derived : Base {
  using Base::Base;
  auto modify() -> void {
    member += 2;
  }
};
```

```
auto modifyAndPrint(Base base) -> void {
  base.modify();
  base.print(std::cout);
}

auto main() -> int {
  Derived derived{25};
  modifyAndPrint(derived);
}
```

```
Output:
26
```

Problems with Member Hiding

- **Member functions in derived classes hide base class member with the same name, even if different parameters are used**
  - Can be problematic, esp. with const/non-const
- **Example: `Derived::modify(int)` hides `Base::modify()`**

```
struct Base {
  int member{};
  explicit Base(int initial);
  virtual ~Base() = default;
  virtual void modify();
};
```

hides

```
struct Derived : Base {
  using Base::Base;
  void modify(int value) {
    member += value;
  }
};
```

```
auto main() -> int {
  Derived derived{25};
  derived.modify();
}
```

Resolution for Hidden Members

- **By "using" the base class' member the hidden name(s) become visible**

```
using Base::modify;
```

- **This enables a call to `derived.modify()`**

```
struct Base {
  int member{};
  explicit Base(int initial);
  virtual ~Base() = default;
  virtual void modify();
};
```

```
struct Derived : Base {
  using Base::Base;
  using Base::modify;
  void modify(int value) {
    member += value;
  }
};
```

```
auto main() -> int {
  Derived derived{25};
  derived.modify();
  modifyAndPrint(derived);
}
```

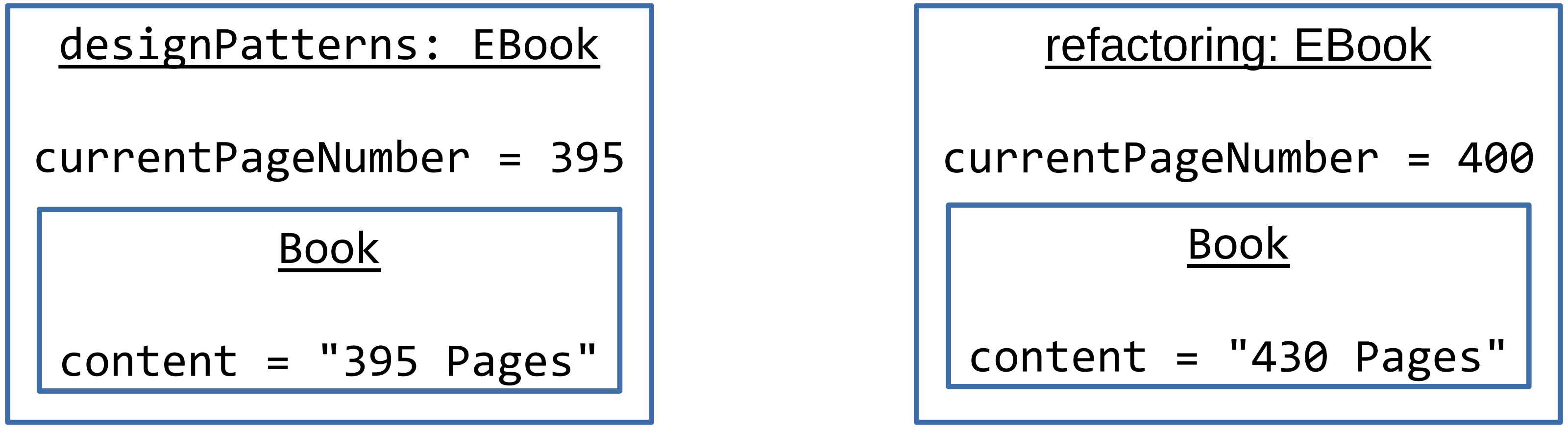
- **Assignment cannot be implemented properly for virtual inheritance structures**

```
struct Book {
  explicit Book(std::vector<Page> pages) :
    pages{pages}{}
  virtual Page currentPage() const -> Page  = 0;
protected:
  std::vector<Page> pages;
};

struct EBook : Book {
  using Book::Book;
  auto openPage(size_t pageNumber) -> void;
  auto currentPage() const -> Page;
private:
  size_t currentPageNumber{1};
};
```

```
void readBook(Book book);

int main() {
  EBook designPatterns{"..."};
  readBook(designPatterns);

  EBook refactoring{"..."};
  Book & some = designPatterns;
  some = refactoring;
}
```

- **The assignment to the reference of the base class overwrites the Base part of the derived object**

```
EBook designPatterns{writeEbook(395)};
EBook refactoring{writeEbook(430)};
refactoring.openPage(400);
Book & some = refactoring;
some = designPatterns;
readPage(some.currentPage());
```



- **You can declare the copy-operations as deleted**

```
struct Book {
  //...
  auto operator=(Book const & other) -> Book & = delete;
  Book(Book const & other) = delete;
};

struct EBook : Book {
  //...
 EBook(EBook const & other) :
    Book{pages},
    currentPageNumber{other.currentPageNumber}{}
  auto operator=(EBook const & other) -> EBook & {
    pages = other.pages;
    currentPageNumber = other.currentPageNumber;
    return *this;
  }
};
```

```
void readBook(Book book);

auto main() -> int {
  EBook designPatterns{"..."};
  readBook(designPatterns);

  EBook refactoring{"..."};
  Book & some = designPatterns;
  some = refactoring;
  EBook copy = designPatterns;
  copy = refactoring;
}
```

- **You should only apply inheritance and virtual member functions if you know what you do**
- **Do not create classes with virtual members by default**
- **If you design base classes with polymorphic behavior, understand the common abstraction that they represent**
  - Do not provide too many members or too few
  - Extract from existing class(es) the base after you see the commonality arise

- **Follow the Liskov Substitution Principle**
  - Base class states must be valid for subclasses
  - Do not break invariants of the base class
  - Invariant signature: Member functions in subclasses must accept the same argument types as the base class (C++)
  - Covariant return type: Return values must be inside the base class member function's range
  - Don't change semantics unexpectedly

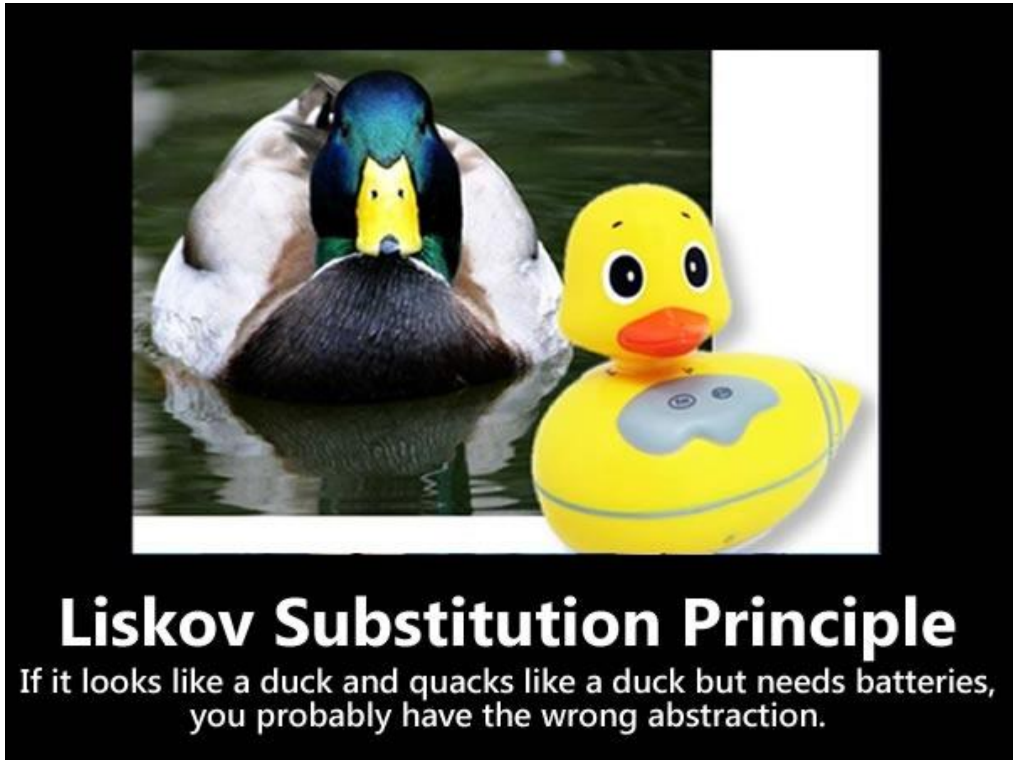


Image Source: http://www.globalnerdy.com/wordpress/wp-content/uploads/2009/07/liskov_substitution_principle.jpg

Summary

- **Three use cases:**
  - Inherit features from empty mix-in classes
  - Adapt features of a base class with a data-less subclass
  - Dynamic polymorphism
- **Beware of unwanted member hiding**
- **Avoid object slicing**
- **Mark Destructors virtual if you have any other virtual member function**